Probing Quark-Gluon Interactions with Transverse Polarized Scattering

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We have extracted QCD matrix elements from our data on doubly polarized inelastic scattering of electrons on nuclei. We find the higher twist matrix element $\tilde{d}_2$, which arises strictly from quark-gluon interactions, to be unambiguously non zero. The data also reveal an isospin dependence of higher twist effects if we assume that the Burkhardt-Cottingham Sum rule is valid. The fundamental Bjorken sum rule obtained from the a_0 matrix element is satisfied at our low momentum transfer.

Polarized deep inelastic scattering (DIS) of leptons on nucleons has helped to establish the modern understanding of nucleon structure. Measurements of the longitudinal nucleon spin structure function (SSF) g_1 in inclusive doubly polarized DIS, where only the final lepton is detected, have revealed that the nucleon spin does not result from the naive sum of the spins of its three valence quarks. Rather, contributions from sea quarks, gluon spin and orbital angular momentum seem to be required [1–3]. DIS is well understood at high energies, when the virtual photons exchanged between the incident beam and the target illuminate the nucleon constituents as the asymptotically free quarks of QCD. This is the regime of small separations between quarks and gluons, which is best tested with short wavelength electromagnetic probes. But the processes that polarized DIS explores are dominated by leading order terms in the expansion of g_1 that are related to the non-interacting partonic

description of QCD. For a full understanding, the interactions among nucleon constituents must also be probed by looking into contributions beyond leading order, which grow in importance at lower energies. Of particular interest are the so called 'higher twist' terms, which measure correlations among partons (quarks and gluons), and offer unique perspectives on the phenomenon of confinement inside nucleons and other hadrons.

Access to these subleading interactions is possible with transverse polarized inelastic scattering. In this configuration, the target spin is held orthogonal to the incident lepton spin, and the g_2 spin structure function dominates compared to g_1 [4]. QCD matrix elements that arise from multi-parton correlations can be extracted directly from moments of g_2. However, this approach has been limited due to the technical challenges involved in aligning proton spins at 90° relative to the beam. As we detail below, we have carried out a complete measurement of

the longitudinal and transverse inclusive SSF's g_1 and g_2 of the proton and deuteron, with the goal of extracting matrix elements related to quark-gluon, qg, interactions.

The Operator Product Expansion (OPE) [5] relates the moments of the SSF's to reduced quark and gluon matrix elements representing the multi-parton correlations that lead to confinement. This perturbative approach to QCD is formulated in terms of the Cornwall-Norton (CN) moments [6]:

$$\Gamma_{1,2}^{(n)}(Q^2) = \int_0^1 dx \; x^{n-1} g_{1,2}(x, Q^2) \qquad (1)$$

where $x = Q^2/2M\nu$ is the Bjorken scaling variable, Q^2 is the four-momentum transfer squared of the scattering process, M the nucleon mass, and ν the energy transfer. Conventionally, the index $n = 1$ is not displayed.

In the OPE, the CN moments are expanded in a power series in $1/Q^{(\tau-2)}$ of increasing 'twist' τ, which is defined as the mass dimension minus the spin n of the corresponding QCD operator [5]. The leading twist-2 terms map to the successful predictions of the parton model, such as the Q^2-independence of the structure functions up to logarithmic corrections. Higher twist (HT) corrections arise from the non-perturbative multiparton interactions, whose contributions at low energy increase as $1/Q^\tau$, reflecting confinement. Specifically, twist-3 represents qgq correlations, so a non-zero result at a given Q^2 for the term representing twist-3 signals a departure from the non-interacting partonic regime.

Studies of higher twist effects [7–11] have typically focused on the CN moments $I(Q^2) = \int_0^1 dx \; x^2 \, (2g_1 + 3g_2)$ and $\Gamma_1(Q^2)$, in order to extract the twist-3 and twist-4 matrix elements. However, as recently stressed in [6, 12], this approach is only appropriate when terms of purely kinematic origin, known as 'target mass corrections' (TMC) [13–18] for their connection to the finite nucleon mass, can be neglected. These terms, of order $\mathcal{O}(M^2/Q^2)$, are formally related to twist-2 operators and must be cleanly separated from the desired dynamical higher twists. $I(Q^2)$ is often labeled 'd_2' in the literature, although, as discussed below, it is not equivalent to the HT matrix element indicated by the same symbol.

As emphasized in [12], dynamical HT can be extracted to order $\mathcal{O}(M^8/Q^8)$ by using Nachtmann moments [16, 19], which depend on the scaling variable $\xi = 2x/(1 + \sqrt{1 + (2xM)^2/Q^2})$. This variable extends scaling as x approaches 1, for data measured at low Q^2. The Nachtmann moments are defined as

$$M_1^n(Q^2) \equiv \frac{1}{2}\tilde{a}_{n-1} \equiv \frac{1}{2}a_n E_1^n = \int_0^1 \frac{dx}{x^2} \xi^{n+1}$$

$$\left[\left\{ \frac{x}{\xi} - \frac{n^2}{(n+2)^2} \frac{M^2 x \xi}{Q^2} \right\} g_1 - \frac{4n}{n+2} \frac{M^2 x^2}{Q^2} g_2 \right] \qquad (2)$$

$$M_2^n(Q^2) \equiv \frac{1}{2}\tilde{d}_{n-1} \equiv \frac{1}{2}d_n E_2^n = \int_0^1 \frac{dx}{x^2} \xi^{n+1}$$

$$\left[\frac{x}{\xi} g_1 + \left\{ \frac{n}{n-1} \frac{x^2}{\xi^2} - \frac{n}{n+1} \frac{M^2 x^2}{Q^2} \right\} g_2 \right] \qquad (3)$$

	Γ_1^p	Γ_1^d	$\tilde{d}_2^p$	$\tilde{d}_2^d$
f	4.9	5.1	4.9	5.1
RC	3.2	4.0	9.5	4.5
F_1	3.0	4.0	3.0	4.0
R	0.9	1.8	1.2	2.8
$P_b P_t$	1.6	1.6	5.2	3.1
Q^2 dependence	0.33	0.1	4.3	0.3
Total	6.8	8.0	13.0	8.9

TABLE I. Measured integral systematic uncertainties (in %) arising from the target dilution factor f, radiative corrections RC, the F_1 and R data fits, beam and target polarizations P_b and P_t, and the evolution of our data fit to constant Q^2.

Here, the a_n (d_n) represent twist-2 (-3) matrix elements, while the E_2^n are the corresponding Wilson coefficients, which contain logarithmic QCD corrections. For convenience, these corrections are absorbed into the definition of the effective matrix elements $\tilde{a}_n$ and $\tilde{d}_n$. The index runs over $n = 1, 3, \ldots$ for M_1, and $n = 3, 5, \ldots$ for M_2. When $Q^2 \gg M^2$, the Nachtmann moments simplify:

$$M_1^1(Q^2) \to \Gamma_1(Q^2), \qquad 2M_2^3(Q^2) \to I(Q^2) \qquad (4)$$

Consequently, deviations from unity of the ratio of Nachtmann to CN moments give a quantitative measure of the TMCs at finite Q^2:

$$R_1(Q^2) = \frac{M_1^1(Q^2)}{\Gamma_1(Q^2)}, \qquad R_2(Q^2) = \frac{2M_2^3(Q^2)}{I(Q^2)} \qquad (5)$$

The leading twist-2 contribution to g_2 can be determined from g_1 via the Wandzura-Wilczek relation [27]:

$$g_2^{\text{ww}}(x, Q^2) \equiv -g_1(x, Q^2) + \int_x^1 y^{-1} g_1(y, Q^2) dy \qquad (6)$$

So any twist-3 effects arise entirely from $\overline{g}_2 = g_2 - g_2^{\text{ww}}$.

Experiment E01-006 was conducted in Hall C of the Thomas Jefferson National Accelerator Facility by the Resonance Spin Structure (RSS) collaboration. We measured the parallel and perpendicular double spin asymmetries $A_\parallel$ and $A_\perp$ in the scattering of 100 nA polarized 5.755 GeV electrons on polarized protons and deuterons. Scattered electrons were detected at an angle of $13.15°$ using the Hall C High Momentum Spectrometer. The kinematic coverage in invariant mass was $1.090 < W < 1.910$ GeV, corresponding to $x_0 = 0.316 < x < x_{\max} = 0.823$, at an average four-momentum transfer of $\langle Q^2 \rangle = 1.28 \pm 0.21$ GeV^2. Systematic uncertainties are detailed in Table I, with more details in [20] and [21].

The SSFs were extracted from the measured asymmetries using a fit to the ratio of longitudinal to transverse cross sections R [22] and the unpolarized structure function F_1 [22], based primarily on data measured previously in Hall C. The standard formulas and procedure used to obtain $A_\parallel, A_\perp$ and the SSFs from the data are detailed in [1] and [20]. Simultaneous determination of both SSFs
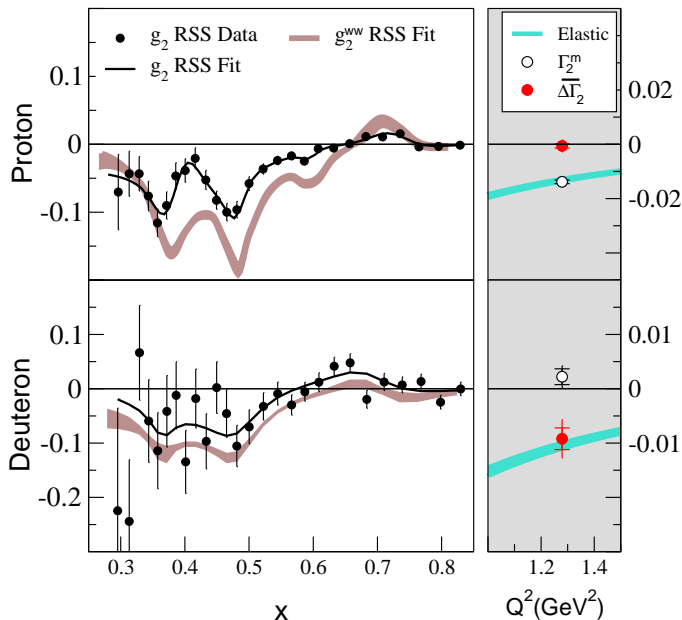
FIG. 1. **Left-top:** RSS proton g_2 data [20], along with the RSS fit [20]. The shaded curve is g_2^{ww} evaluated from the RSS fit. **Left-bottom:** RSS deuteron g_2 data, and similar curves as above. **Right-top:** The open circle is the measured RSS proton $\Gamma_2^m(Q^2)$ data. The full circle is $\Delta\overline{\Gamma}_2(Q^2)$. The inner (outer) error bars represent statistical (total) uncertainty. The shaded curve is the elastic contribution to $\Gamma_2(Q^2)$. **Right-bottom:** Same as above, but for deuteron.

allowed us to evaluate the moments without model input for g_2, as was necessary in some previous analyses [9].

The moments reported herein are evaluated at $\langle Q^2 \rangle = 1.28$ GeV^2, and have been decomposed into contributions from the measured resonance region $x_0 < x < x_{thr}$ (labeled with 'm'), the well known $x = 1$ elastic ('el') contribution, and the unmeasured ('u') portion below x_0. We note that the small difference between our experimental x_{max} and the nucleon inelastic threshold x_{thr} has negligible impact on the integrated results. We have used fits [20] to our data to evaluate the moments in the measured region. The nucleon elastic contribution was calculated using the form factor parameterizations of [23]. Relative uncertainties of 5, 1, 14, and 2.5% have been assumed for the electromagnetic form factors $G_{E,M}^P$ and $G_{E,M}^N$ respectively. For the deuteron, $x = 1$ represents quasielastic scattering, the strength of which we estimate by combining the nucleon elastic contributions using the D-state correction discussed below. The deuteron nuclear elastic contribution is negligible here. We have also evaluated the neutron and non-singlet (proton - neutron) moments by using the relation [24] $\Gamma^n = \Gamma^\Sigma - \Gamma^p$, where the singlet $\Gamma^\Sigma = \Gamma^d/\gamma_D$, and $\gamma_D \simeq 0.926 \pm 0.016$ [25] is the D-state correction to the deuteron wave function. The uncertainty arising from this approach is estimated [26] to be $\mathcal{O}(1\%)$. The singlet and non-singlet results assume negligible heavy quark contributions.

Table II provides numerical values for the moments. The ratio R_2 differs significantly from unity, indicating large unwanted twist-2 kinematical contributions to $I(Q^2)$. The full results for the matrix element $\tilde{d}_2$ indicate clear twist-3 at more than 6σ for the proton and 3σ for the neutron. These non-vanishing results unambiguously indicate the presence of qgq correlations. Their magnitudes can be used in comparing with nucleon models.

The values of $I(Q^2)$ and $\tilde{d}_2$ for $x < x_0$ were estimated to be zero, with a systematic error described below. In this unmeasured region, $\xi \approx x$ and the CN and Nachtmann truncated moments converge, so there is little difference between $I(Q^2)$ and $\tilde{d}_2$. $I(Q^2)$ is expected to be small in this unmeasured region, because of the decreasing importance of higher twists at low x, and the strong suppression due to the x^2 weighting of the integral. This assumed low x behavior is supported by our data. Figure 1 (left) displays the $x-$dependence of the measured g_2 structure function. It is clear that $\overline{g}_2$ is nearly constant and consistent with zero within errors for the proton, near the low end of our measured range $x_0 < x \lesssim 0.37$. The deuteron data shows a similar behavior, different from zero only at the one σ (statistical) level. Neutron data [28] at $x \sim 0.2$ and similar Q^2 are also consistent with $\overline{g}_2 \cong 0$. We take the error on $\overline{g}_2$, evaluated at x_0, $\delta\overline{g}_2$, as a conservative upper limit for the integrand of $I(Q^2)$ in the unmeasured low x region. For the proton, we determined this upper limit by assuming a constant extrapolation of the value of $\delta\overline{g}_2(x_0)$ down to $x = 0$. For the deuteron, we evaluated both a linear and constant extrapolation, averaged both assumptions and added quadratically one-half their difference as 'model' error to the $\delta\overline{g}_2^d$ fit error to obtain the value in Table II. A divergence of g_2 as $x \to 0$ could invalidate this assumption. Such a possible divergence for $x \lesssim 0.001$ was discussed in [29]. Normalizing the low x dependence of $\overline{g}_2$ given in [29] to our $\delta\overline{g}_2$ estimates, we find the additional contribution to be negligible.

It is instructive to compare our twist-3 results to previous measurements. SLAC E155 [1] reported an evaluation of $I(Q^2)$ at $\langle Q^2 \rangle = 5$ GeV^2. We have corrected those results for TMCs [12], to obtain 0.0028 ± 0.0015 and 0.0072 ± 0.0044 for the proton and neutron, respectively. For direct comparison, we performed a pQCD evolution [30] from RSS to the SLAC kinematics. At LO, we find $\tilde{d}_2^p = 0.0021 \pm 0.0006$ and $\tilde{d}_2^n = 0.0031 \pm 0.0038$, which are consistent with the E155 results. The elastic contribution [23] at these kinematics is smaller than the uncertainties and is not included in the results of this paragraph. NLO corrections [31] to our data have been calculated and will be discussed in a future publication.

Twist-3 effects also manifest in the first moment of g_2. The Burkhardt-Cottingham (BC) sum rule [32] predicts that Γ_2 vanishes for all Q^2. This sum rule can be derived from the unsubtracted dispersion relation for the virtual-virtual Compton scattering amplitudes, in an analogous fashion to the more famous GDH and Bjorken sum rules. It provides a remarkably clean tool to investigate nucleon

x-range		Proton			Deuteron			Neutron		Non-Singlet	
		Value	Stat	Syst	Value	Stat	Syst	Value	Total	Value	Total
$0 < x < x_0$ (unmeasured)	M_1^1	0.0676	⋯	0.0069	0.0274	⋯	0.0104	-0.0381	0.0132	0.1057	0.0178
	Γ_1	0.0683	⋯	0.0069	0.0280	⋯	0.0099	-0.0381	0.0127	0.1065	0.0176
	$\tilde{d}_2$	0.0	⋯	0.0008	0.0	⋯	0.0013	0.0	0.0016	0.0	0.0021
	I	0.0	⋯	0.0008	0.0	⋯	0.0013	0.0	0.0016	0.0	0.0021
$x_0 \leq x < x_{thr}$ (measured)	M_1^1	0.0330	0.0005	0.0022	0.0290	0.0010	0.0023	-0.0016	0.0036	0.0346	0.0054
	Γ_1	0.0351	0.0005	0.0024	0.0315	0.0011	0.0025	-0.0010	0.0039	0.0361	0.0058
	$\tilde{d}_2$	0.0037	0.0004	0.0005	0.0048	0.0008	0.0004	0.0015	0.0012	0.0022	0.0016
	I	0.0057	0.0006	0.0007	0.0082	0.0013	0.0007	0.0031	0.0019	0.0026	0.0026
$x = 1$ (elastic)	M_1^1	0.0287	⋯	0.0006	0.0338	⋯	0.0012	0.0078	0.0005	0.0208	0.0008
	Γ_1	0.0351	⋯	0.0010	0.0373	⋯	0.0015	0.0051	0.0007	0.0300	0.0012
	$\tilde{d}_2$	0.0067	⋯	0.0008	-0.0021	⋯	0.0010	-0.0090	0.0007	0.0157	0.0011
	I	0.0306	⋯	0.0025	0.0088	⋯	0.0029	-0.0212	0.0019	0.0518	0.0031
$0 \leq x \leq 1$ (Total)	M_1^1	0.1293	0.0005	0.0073	0.0902	0.0010	0.0108	-0.0318	0.0137	0.1611	0.0187
	Γ_1	0.1385	0.0005	0.0074	0.0968	0.0011	0.0103	-0.0340	0.0134	0.1725	0.0185
	$\tilde{d}_2$	0.0104	0.0004	0.0013	0.0027	0.0008	0.0017	-0.0075	0.0021	0.0179	0.0029
	I	0.0364	0.0006	0.0027	0.0170	0.0013	0.0032	-0.0180	0.0031	0.0544	0.0045
$0 \leq x \leq 1$	R_1	0.933		0.003	0.932		0.012	0.936	0.037	0.934	0.008
	R_2	0.286		0.014	0.159		0.078	0.415	0.045	0.329	0.025

TABLE II. RSS Moments evaluated at $\langle Q^2 \rangle = 1.28$ GeV^2. The ratio $R_1 = M_1^1/\Gamma_1$ and $R_2 = \tilde{d}_2/I$.

structure, since it is free from both QCD radiative corrections and TMCs [33]. Initial measurements by the E155 collaboration [1] found a 2σ inconsistency with the proton BC sum rule at large Q^2, while the same group found the deuteron sum rule to hold. Later measurements [3, 7] at lower momentum transfer found agreement with both the neutron and ^{3}He BC sum rules.

The leading twist g_2^{ww} satisfies the BC sum rule exactly, so any violation must arise from higher twist effects. For convenience we split the full integral as:

$$\Gamma_2 = \Gamma_2^{\mathrm{ww}} + \overline{\Gamma}_2 + \Gamma_2^{el}$$
$$= \overline{\Gamma}_2^u + \overline{\Gamma}_2^m + \Gamma_2^{el} \qquad (7)$$

where the overbar signifies removal of the leading twist contribution, and we have made use of the fact that $\Gamma_2^{\mathrm{ww}} \equiv 0$ by definition. The elastic contribution is well known, as displayed in Fig. 1, and we can evaluate $\overline{\Gamma}_2^m$ directly from our own data. $\overline{\Gamma}_2^u$ is pure higher twist, and cannot be directly determined, due to the lack of low x g_2 data. However, the difference,

$$\Delta\overline{\Gamma}_2 \equiv \Gamma_2 - \overline{\Gamma}_2^u \qquad (8)$$

depends only on measured data. A significant non-zero result for this quantity would indicate a higher twist contribution to the integral in the region $x < x_0$, assuming of course, that the BC sum rule holds. We find that the proton results are consistent with vanishing HT effects at low x. On the other hand, the singlet results indicate the need for significant HT contributions to Γ_2 at low x, if the BC sum rule is to be satisfied. This could indicate an isospin dependence of the BC sum rule, or alternatively, a modification to the sum rule due to nuclear effects.

Nachtmann moments are also useful for obtaining leading twist matrix elements free of TMCs. The a_0 non-singlet matrix element corresponds to the lowest moment Γ_1^{p-n} of the isovector nucleon g_1, which is related to the nucleon axial charge g_A via the Bjorken sum rule [34]. This relation is a direct consequence of QCD, and experimental tests [1, 2] of the sum rule have played a critical role in confirming QCD as the correct theory of the strong interaction. The target mass corrections to Γ_1 given by the ratio R_1 are small at our kinematics, due to a combination of dominant contributions from the region below our lowest measured x_0, and the nearly identical values of x and ξ in that region. It is interesting to note that $R_1 \approx 93\%$ for all targets, when the elastic contribution is included. The M_1^1 non-singlet result including the elastic part (0.161 ± 0.019) is in excellent agreement with theory: Ref. [35] predicts 0.212, which reduces to 0.155 after application of the next to next-to-leading order corrections [36] appropriate at our Q^2. For the g_1 integrals, the contribution from the $x < x_0$ region was calculated from Regge-inspired fits to SLAC g_1^p and g_1^d data [1] within a band $Q^2 = 1.3 \pm 0.3$ GeV^2. We find $g_1 = ax^b(1-x)^3(1+c/Q^2)$ with $a = 0.392 \pm 0.254$, $b = 0.0676 \pm 0.084$, $c = 0.0636 \pm 0.681$ for the proton, and $a = 1.778 \pm 1.971$, $b = 0.739 \pm 0.407$, and $c = -0.786 \pm 0.0256$ for the deuteron.

In summary, we have measured the spin structure function moments of the proton, deuteron and neutron in the resonance region. The kinematic weighting of higher moments suppresses contributions from the low x region, thus minimizing the systematic uncertainty of this unmeasured piece of the integral. Our analysis indicates a large TMC contamination of the CN moment $I(Q^2)$, which has often been used to determine the magnitude of higher twist effects. The alternate Nachtmann moment $\tilde{d}_2$ minimizes TMCs and allows a clean extraction of the twist-3 reduced matrix element. The previously undetermined $\tilde{d}_2$ provides unambiguous evidence of dynamical

	Proton			Deuteron			Neutron		Non-Singlet	
	Value	Stat	Syst	Value	Stat	Syst	Value	Total	Value	Total
Γ_2^{el}	-0.0132	$\cdots$	0.0004	-0.0219	$\cdots$	0.0009	-0.0105	0.0005	-0.0027	0.0007
Γ_2^{m}	-0.0138	0.0007	0.0009	-0.0107	0.0012	0.0009	0.0022	0.0020	-0.0160	0.0028
$\overline{\Gamma}_2^{m}$	0.0126	0.0008	0.0020	0.0129	0.0016	0.0018	0.0013	0.0034	0.0113	0.0051
$\Delta\overline{\Gamma}_2$	-0.0006	0.0008	0.0021	-0.0090	0.0016	0.0020	-0.0092	0.0035	0.0086	0.0051

TABLE III. The higher twist $\Delta\overline{\Gamma}_2 = \Gamma_2 - \overline{\Gamma}_2^{u}$ evaluated at $\langle Q^2 \rangle = 1.28$ GeV^2.

twist-3 effects, which arise from quark-gluon interactions. The first moment of g_2 indicates an isospin dependence of HT effects in the region of small Bjorken scaling variable, assuming that the BC sum rule holds. After nearly thirty years of spin-dependent investigations, the g_2^p structure function remains largely unknown. But the data reported here and future analyses [37] will shed light on this fundamental nucleon observable.

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